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EUROPA LANDER TRAJECTORY DESIGN: CASE STUDIES FOR THE DIRECT-TO-EARTH ARCHITECTURE

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This paper presents interesting phasing problems that came up in support of design studies for a potential Europa Lander mission. Recent system trades were performed after the Mission Concept Review in fall 2017, when the NASA board recommended the Europa Lander project design a Direct-to-Earth architecture, i.e. where the Lander would communicate directly to the Earth, without data relay from the carrier vehicle.

Two studies in particular required an original trajectory design concept. In the first study, which considered a bi-propellant system for the lander, we designed an ultra- low-radiation endgame with separate Europa orbit insertion (EOI) and de-orbiting maneuvers for the Descent Vehicle (DOV), and a ballistic Ganymede-impact transfer for the carrier. In the second study, we analyzed trajectories to use Clipper as a data-relay spacecraft during Europa landing.

NOMENCLATURE

α Pump angle

κ Crank angle

$n : m$ Resonant ratio used to define the period of the spacecraft orbit around Jupiter. n is the number of spacecraft revolutions and m is the number of moon's revolutions.

$\mathbf{v}_\infty, v_\infty$ Spacecraft hyperbolic velocity relative to a moon, and its magnitude

CS Carrier stage

DOV Descent orbit vehicle

EOI Europa orbit insertion

LS Landing site

$N - GE$ Ganymede-Europa quasi-Hohmann transfer, with N full revolutions

TID Total ionizing dose (kRad).

TOF Time of flight

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INTRODUCTION

Europa is one of the most interesting bodies in the solar system as it possesses all the ingredients for life.[1] Over the last decades, several missions have been proposed for its exploration, either with Europa flybys,[2–5] orbiters,[6,7] or landers.[7,8] An Europa lander mission is the only mission concept to provide in-situ biosignature,[?] but its trajectory design is even more challenging than for other architectures.[?]

Europa is deep inside the gravity well of Jupiter, in a region of the magnetosphere with many trapped high-energy particles, and any spacecraft planning to orbit or land on that moon should budget a large mass of propellant and radiation shielding. At the same time, any mission element that would land or otherwise have sufficiently large probability to impact the surface should be sterilized to avoid contaminating the moon with traces of life carried over from Earth. To mitigate these contrasting requirements, Europa lander architectures typically include a carrier and a lander vehicle; the lander vehicle performs the large maneuvers for de-orbiting and landing. The carrier instead is disposed of by either impacting another moon, or entering a stable orbit (around Europa or Jupiter), where it is sterilized by the radiation environment over the course of several years. Often the carrier acts as a data relay for the short duration of the lander mission. A number of Europa lander mission concepts have been proposed in the past;[9,10] the latest Europa Lander mission concept implements a Direct-to-Earth architecture, i.e. where the Lander would communicate directly to the Earth, and with a simpler, lighter carrier with no orbit control nor telecommunication capabilities.

This paper presents two interesting problems that came up in support of design studies for this recently proposed DTE architecture. In the first study, which consider a bi-propellant system for the lander, we designed an ultra- low-radiation endgame with separate Europa orbit insertion and de-orbiting maneuvers for the Descent Vehicle (DOV), and a ballistic Ganymede-impact transfer for the carrier. In the second study, we analyze trajectories to use Clipper as a data-relay spacecraft during Europa landing. In both cases, the design is particularly complex because it involves the optimization of separate trajectories with tightly coupled constraints.

EUROPA LANDER TRAJECTORY DESIGN

An Europa lander trajectory includes an interplanetary transfer to Jupiter and a Jupiter orbit insertion maneuver into a 200-day period orbit. The trajectory then starts a series of flybys (moon tour) to reduce the spacecraft period and its velocity relative to Europa (v_∞), leading to the EOI maneuver. To minimize the total costs (Δv , TOF, and TID), the tour utilizes mainly Callisto and Ganymede flybys and first approaches Europa with a GE transfer. Opportunities for a GE transfer repeat once every week (Europa-Ganymede synodic), and its geometry precesses 6^o each time relative to the Sun, rotating 360^o in 14 month (see Fig. 1). To increase the number of opportunities, additional revolutions are added to the transfer (N-GE) at the additional cost of 80 kRad per revolution. *

In some Europa lander tours, the GE is followed by a $v_\infty-$leveraging endgame[11,12] to further reduce the v_∞ at Europa, at the expenses of a larger TID. The first study of this paper presents a strategy for a low-TID mission without the $v_\infty-$leveraging endgame; the higher Δv cost at EOI is mitigated by separating the CS from the DOV.

*Although for N¿1 the opportunities almost repeat because the GE period is commensurable to Ganymede's period.

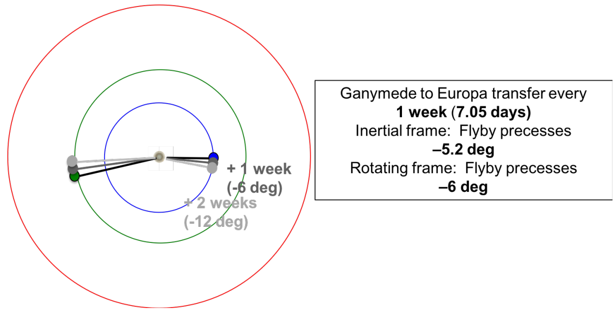

Figure 1. GE transfer opportunities and their geometry in a rotating frame (with fixed Jupiter-Sun direction)

Flyby parametrization with pump and crank angles

In this paper, flybys are parametrized by the v_∞ magnitude and by the direction of the incoming and outgoing asymptotes, described in spherical coordinates by the incoming and outgoing crank (κ) and pump (α) angles.[13] If $\alpha_{In} = \alpha_{Out}$, the spacecraft period before and after the flyby remains the same, and the flyby is called crank-only. Because the moons are tidally locked, it can be shown that the closest approaches of crank-only flybys are near the prime meridian or anti-meridian.[4,13]

LS and LST constraints

The design of an Europa lander tour should guarantee landing access to a wide region of potential LS (landing region) at some desired illumination conditions expressed in LST. The landing region is typically within 60^o latitude from the equator and should overlap, as much as possible, the reconnaissance region from Clipper (shown in figure 2). Since Clipper makes extensive use of crank-only flybys,[5] the high-resolution images used for reconnaissance are mainly around the prime meridian or anti-meridian.

Illumination conditions at the landing site can be mapped back to the GE geometry,[7] and are translated into constraints on the landing period - the number of weeks when the GE transfers occur at the right geometry. For example, a $\pm 1h$ window around a desired LST is mapped to a 5 weeks landing period.

LOW TID ENDGAME FOR BI-PROP ARCHITECTURE

As part of the DTE trade studies, a liquid-propulsion only architecture was proposed. Such propulsion system would allow a new trajectory strategy, shown schematically in Fig. 3, where the CS would flyby Europa and ballistically hit Ganymede, while the DOV would separate shortly before closest approach, to then perform (1) EOI into a circular orbit, (2) pericenter drop and (3) de-orbit burn.

This strategy would reduce the propellant mass on the CS, which would not need to execute EOI. Also, any LS site below the capture orbit can be targeted by changing the timing of the pericenter drop maneuver within one or two revolutions (beyond which the delivery dispersion grows too large and cannot be corrected). Multiple approach trajectories must be designed to target different LS within the landing region, all branching off the same tour sometime after the LS selection. The trajectories should have at 50-km altitude approach at Europa with low v_∞. At the same time,

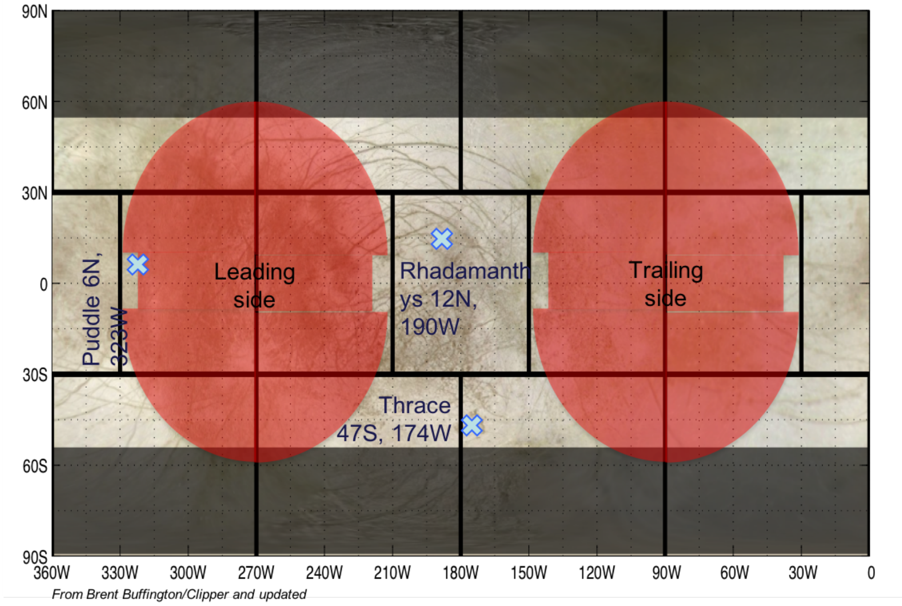

Figure 2. High-resolution reconnaissance region from Clipper (source: B.Buffington)

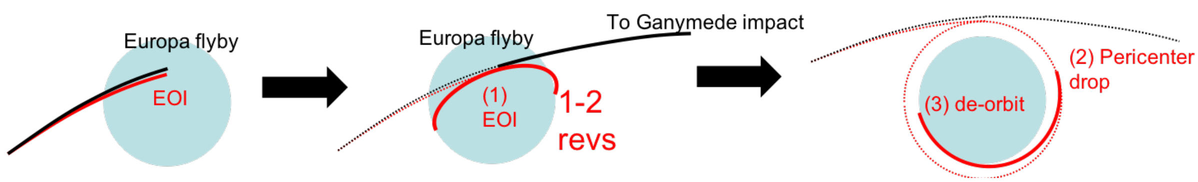

Figure 3. Carrier flyby and separate EOI and de-orbit maneuvers for the lander

the CS post-flyby trajectory should impact Ganymede ballistically and be robust to flyby delivery errors, since the CS possess no orbit control capabilities after the DOV separation.

N-GEG transfers

The type of transfer that can solve all these requirements is illustrated in Figure 4 and referred to as GEG (Ganymede-Europa-Ganymede). GEG starts with a 7-day period orbit (1), and uses a Ganymede flyby (2) to place the spacecraft into a (3) GE transfer. At Europa approach, the DOV would separate and execute the EOI (4) into a 50 km altitude circular orbit, followed by the pericenter drop maneuver to decrease the altitude to 5 km and initiate the descent and landing maneuvers[?] (not discussed in this paper). At the same time, the CS would flyby Europa at 50 km altitude (4).

We note that the period of GE is almost 3:4 resonant with Ganymede period (and 3:2 resonant with Europa period), so if no Europa flyby was to occur, the spacecraft would return naturally to the vicinity of Ganymede after four revolutions. The Europa flyby is then designed to be a crank-only flyby, not to impact the orbital period, and also shadows a typical Clipper flyby.

The GEG transfer example in Figure 4 is only one of the four possible variations obtained using N-GE, $N = 0, 1, 2, 3$, shown schematically in table 5. GEG transfers can save 1 Mrad TID com-

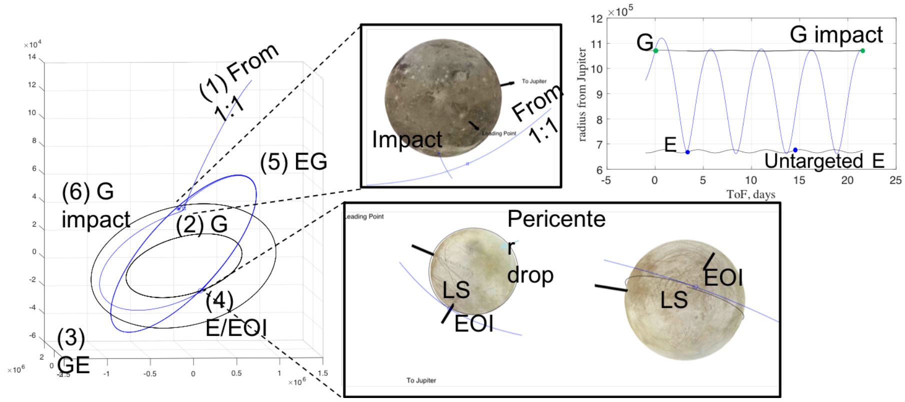

Figure 4. Example 0-GEG endgame with ballistic disposal

N	TYPE	TID kRad	NOTES
0	Untargeted flyby	~40	Not enough feasible solutions to cover the landing region. There is not enough time for a small maneuver in the GE arc, and the few solutions that converge are not robust to delivery errors because of the 3.5 revs to Ganymede impact and the untargeted Europa flyby
1	Untargeted flyby	~120	
2	Targeted flyby	~200	
3	Targeted flyby	~280	Not computed because of high TID

Figure 5. Types of GEG

pared to other options with v_∞-leveraging endgame, while the increased Δv for EOI is mitigated by having it performed on a lower mass (DOV instead of CS+DOV) . The following section show the details of different families of 1-GEG and 2-GEG.

GEG design and analysis

GEG are first searched in patched-conics model with STAR[14] and then optimized in full model with jTOP.[15] We expect ballistic, patched-conic, N-GEG to exist as one-dimensional families, because they can be mathematically described with two equality constraints ($v_\infty \doteq \|\mathbf{v}_\infty^-\| = \|\mathbf{v}_\infty^+\|$, and $\cos\left(\langle \mathbf{v}_\infty^+, \mathbf{v}_\infty^- \rangle / v_\infty^2\right) = f(altitude)$), in three variables (the flyby dates).

Figure 6 on the left shows the result of the STAR search of 1-GEG. Every point represents a trajectory, parametrized by its TOF and by the longitude and latitude at the EOI location. The figure shows different families, which are clustered around either the prime meridian (sub-Jovian approach) or the anti-meridian (anti-Jovian approach). Sub-Jovian approach trajectories are direct, and save on the de-orbiting Δv thanks to the rotation of Europa.

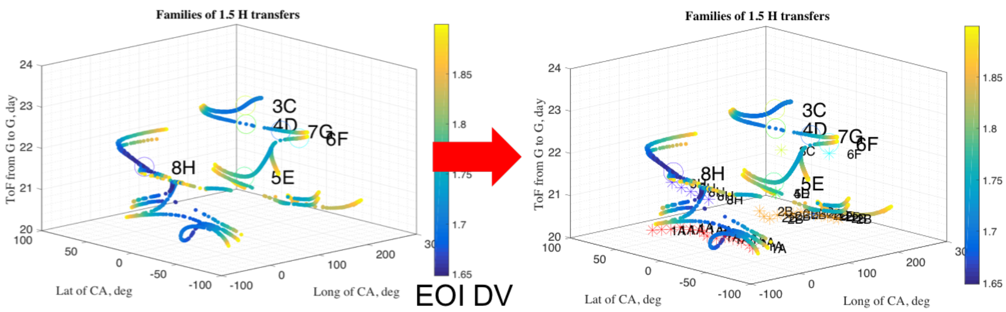

Figure 6. GEG1 families

A representative set of solutions (one per family) is then re-optimized in full model. To increase the number control variables for the optimization, a small impulsive maneuver is added in the GE leg. The period before G1 is fixed to a 1:1 resonance, and the final state at Ganymede impact is bounded to have a sufficiently low osculating pericenter to be robust to delivery errors. When a trajectory converges in the full model with a reasonable Δv, other trajectories in the same family are optimized by continuation, targeting different latitudes at the prime meridian or anti-meridian crossing.

Table 1 shows details about the converged 1-GEG trajectory. The trajectory family is shown in the 5th column. The impact altitude is shown on the right ("Ganymede flyby 2/ alt"), while Column 6 shows the new altitude following a 5-km Europa altitude delivery error; most trajectories with ID 17-32 would miss Ganymede and are excluded from the solution space. Figure 7 shows the robust solutions on the left, and the non-robust solutions on the right. There appears to be a correlation between robustness and whether the flyby is direct or retrograde, but more research should be carried to investigate this.

Column "EOI" of Table 1 shows the Δv of the EOI, and the expected Δv penalty for descent and landing, which is function of the latitude and on whether the approach is prograde and retrograde. The formula for the Δv penalty is presented in the appendix. Overall we budget around 1250 km /s for both Δv combined, while TCM Δv should be as low small as possible (ideally zero) since it must be performed by the CS and DOV.

Figure 8 shows the ground-tracks of the first orbit for all feasible solutions, which nicely overlap the landing region - a consequence of the Europa flyby being a crank-only, like Clipper's. The color shows the change in local solar time along the orbit. Finally Table 2 and Fig. 9 shows the details and the ground-tracks for the 2-GEG transfer.

CLIPPER/LANDER CONCURRENT TOUR DESIGN

A second study explored the possibility of using Clipper as relay spacecraft during the lander de-orbit descent and landing operations (while the high-gain is stacked inside the DOV), and possibly during the 15 min transition phase following the landing, with a second pass 2 weeks later in case of telecom failures. The scope of the work was to assess the feasibility from the trajectory viewpoint, regardless of programmatic considerations. The floor requirement for the data-relay is Clipper flying within 25,000 km of the DOV during the 5 min DDL. The ideal requirement is Clipper flying within 7,600 km during 5 min DDL, and within 10,700 km during transition phase.

Table 1. Converged 1-GEG trajectories in full model

Comm	ID	CASE: 0/180 crossing Long	Lat	Fam	altitutde (km) after 5 km (3s) E1 error	DV cost (m/s) DVtot	TCM	EOI	V rot.	EOI + DDV	untarg. flyby alt (km)	Ganymede flyby 1 vinf (km/s)	alt (km)	Incomig(deg) pump	crank	Outgoing (deg) pump	crank	long wrt Sun	G-E Dlong (deg)	Europa flyby / EOI vinf (km/s)	alt (km)	Incoming (deg) pump	crank	Outgoing (deg) pump	crank	long wrt Sun	E-G2 Dlong (deg)	Ganymede flyby 2 vinf (km/s)	alt (km)	Incoming (deg) pump	crank	Outgoing (deg) pump	crank	long wrt Sun
	1	0	-60	A	-494	1265	9	1240	16	1256	162311	2.28	2214	97	25	120	0	5	130	1.75	48	18	-26	33	104	135	177	1.45	-1670	153	-87	83	146	-48
NOM	2	0	-50	A	-1708	1249	0	1228	21	1249	61465	2.09	927	91	34	124	1	13	132	1.73	48	22	-20	30	109	144	175	1.43	-1881	155	-90	81	122	-41
NOM	3	0	-40	A	-1792	1233	0	1208	25	1233	67466	2.01	849	90	37	126	1	15	134	1.7	48	21	-24	29	129	149	174	1.41	-1879	158	-69	80	128	-37
NOM	4	0	-30	A	-1446	1228	0	1199	29	1228	86868	1.97	820	90	38	127	2	16	136	1.68	48	20	-28	29	148	152	173	1.41	-1877	159	-46	80	135	-35
NOM	5	0	-20	A	-1560	1229	0	1198	31	1228	82665	1.94	814	90	40	128	3	17	137	1.68	48	21	-29	29	166	154	172	1.39	-1854	162	-30	77	136	-34
NOM	6	0	-10	A	-1602	1235	0	1203	32	1235	54963	1.93	660	86	38	129	3	17	136	1.69	48	22	-27	29	-178	154	168	1.31	-2012	173	-26	58	131	-38
BKUP	7	0	0	A	-1570	1245	0	1213	32	1245	124320	2	1429	91	31	127	3	16	135	1.7	48	21	-28	31	-163	151	169	1.36	-1666	167	13	63	103	-40
	8	0	5	A	-1583	1258	20	1206	32	1238	97671	1.92	265	97	57	129	3	17	135	1.69	48	25	-25	29	-151	151	172	1.37	-1631	165	25	64	113	-36
	9	0	10	A	-1588	1278	20	1226	31	1257	88852	1.87	1168	97	47	130	4	17	135	1.72	48	26	-27	31	-141	152	173	1.39	-1631	162	36	64	124	-35
	10	0	20	A	-1796	1272	0	1243	30	1272	111975	2.01	1253	91	33	127	3	16	132	1.75	48	26	-23	33	-130	148	175	1.4	-1976	160	48	55	144	-37
	11	0	30	A	-981	1265	2	1235	28	1263	137573	2.08	1763	97	-31	125	1	14	131	1.74	48	23	-9	32	-125	145	176	1.39	-1636	159	50	75	169	-39
	12	0	40	A	-1230	1285	1	1260	24	1284	174628	2.21	1957	97	-27	122	1	9	128	1.78	48	23	-9	35	-113	137	174	1.37	-1631	159	80	63	168	-48
	13	0	50	A	-1281	1314	4	1290	20	1310	183685	2.31	2147	97	-24	120	0	6	125	1.82	48	25	-7	37	-99	131	175	1.38	-1631	155	102	62	-172	-54
	14	0	60	A	-1324	1363	3	1345	15	1360	158445	2.39	2512	97	-21	119	0	4	121	1.9	48	30	-5	39	-81	125	176	1.46	-1631	149	123	67	-144	-59
NOM	15	180	-60	B	-429	1220	0	1236	-16	1220	394557	1.51	379	74	49	145	40	19	167	1.74	48	36	-100	19	14	-174	152	2.33	-1688	120	-176	107	-85	-21
NOM	16	180	-50	B	-84	1205	0	1226	-21	1205	395369	1.61	627	76	43	140	27	22	165	1.72	48	34	-114	18	16	-173	152	2.33	-1689	120	-176	108	-84	-21
	17	180	-40	B	209	1198	0	1223	-25	1197	386342	1.75	894	80	39	134	17	22	163	1.72	48	31	-127	19	17	-175	153	2.3	-1678	121	-175	107	-84	-23
	18	180	-30	B	467	1195	0	1224	-28	1195	363436	1.92	742	80	31	128	10	19	159	1.72	48	28	-140	21	16	177	155	2.24	-1673	122	-175	105	-82	-27
	19	180	-20	B	763	1204	0	1235	-31	1204	295791	2.2	54	75	26	122	3	9	150	1.74	48	22	-151	25	12	160	161	2.09	-1652	125	-174	103	-76	-39
	20	180	-10	B	525	1217	0	1249	-32	1217	157925	2.45	3835	94	-1	117	1	1	144	1.76	48	18	-160	29	4	145	166	1.97	-2193	127	-175	90	-51	-49
	21	180	0	B	185	1228	0	1261	-33	1228	66873	2.56	3614	94	-7	115	0	-5	141	1.78	48	15	-165	31	-7	136	167	1.98	-2559	127	-179	62	-30	-57
	22	180	10	B	1634	1238	0	1270	-32	1238	23129	2.61	3392	93	-6	115	0	-8	140	1.79	48	14	-164	33	-20	131	163	2.22	-2527	121	177	60	-45	-65
	23	180	20	B	18	1246	0	1276	-31	1246	17076	2.61	3334	93	-7	115	0	-8	140	1.8	48	15	-164	34	-34	132	162	2.21	-2439	121	174	61	-62	-66
DV!	24	180	30	B	14041	1251	0	1279	-28	1251	7224	2.56	3053	94	-11	115	0	-6	142	1.8	48	17	-165	35	-49	137	154	2.23	-2438	121	175	50	-64	-69
	25	180	40	B	338678	1270	0	1294	-24	1270	3725	2.56	3128	94	-11	116	1	-4	144	1.83	48	19	-166	36	-64	140	146	2.53	-2521	116	178	42	-48	-74
	26	180	50	B	439474	1299	0	1319	-20	1299	2507	2.6	3095	94	-10	115	1	-6	144	1.86	48	21	-166	38	-77	138	145	2.65	-2502	114	179	35	-51	-76
	27	180	60	B	371163	1329	0	1345	-15	1329	1782	2.67	2589	94	-14	114	0	-9	143	1.9	48	21	-169	40	-87	134	150	2.59	-2476	115	178	26	-51	-76
	28	180	20	C	1865	1195	0	1225	-31	1195	18746	2.04	205	87	144	129	-178	-83	142	1.72	50	21	-176	29	-37	135	159	2.22	-1679	121	175	78	98	-66
BKUP	29	180	20	D	-737	1203	0	1233	-30	1203	450187	1.42	2964	96	-44	151	-34	25	177	1.73	50	37	144	16	26	-153	146	2.5	-2320	117	-175	77	75	-6
!Same	*30*	*180*	*20*	E	-538	*1205*	*0*	*1236*	*-30*	*1205*	*436011*	*1.5*	*912*	*94*	*-88*	*152*	*-36*	*20*	*179*	*1.7*	*50*	*36*	*142*	*18*	*25*	*-159*	*148*	*2.5*	*-2574*	*118*	*-174*	*45*	*36*	*-11*
	31	180	-45	F	143	1245	0	1266	-22	1245	283099	1.59	2553	96	64	142	38	18	165	1.79	50	38	-100	28	-12	-176	134	2.13	-2130	129	2	42	-72	50
	32	180	-20	G	1219	1205	0	1235	-31	1205	328379	2.09	531	88	42	124	6	13	154	1.74	50	25	-143	24	2	166	159	2.18	-2066	123	-177	38	115	-35
NOM	33	0	0	H	-1550	1220	0	1187	32	1220	82437	1.54	199	91	-135	153	173	-22	174	1.66	50	26	-22	27	-159	152	173	1.36	-1644	165	12	71	128	-35
NOM	34	0	10	H	-1438	1226	0	1195	32	1226	124588	1.6	318	91	-134	149	177	-28	176	1.68	50	26	-17	28	-146	148	173	1.36	-1703	164	30	67	136	-39
NOM	35	0	20	H	-1636	1247	0	1217	30	1247	147738	1.65	453	92	-138	146	177	-34	177	1.71	50	28	-17	31	-128	143	174	1.36	-1934	163	55	58	158	-43
NOM	36	0	30	H	-1691	1227	0	1199	28	1227	134901	1.65	950	90	-145	146	-173	-35	178	1.68	50	26	2	29	-125	143	176	1.36	-2053	163	52	57	167	-41
NOM	37	0	40	H	-1793	1213	0	1188	25	1213	110972	1.65	1234	89	-151	146	-164	-35	179	1.67	50	25	21	27	-123	145	177	1.36	-2118	163	47	56	168	-38

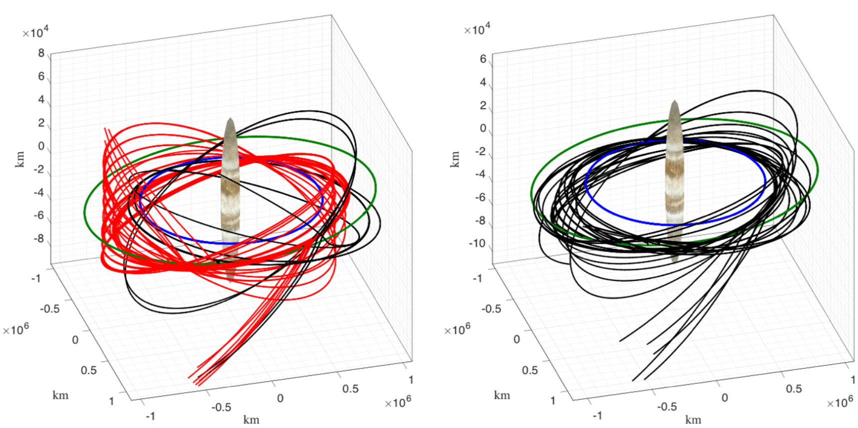

Figure 7. Left: Stable orbits. right: unstable orbits (Black = direct, Red = retrograde)

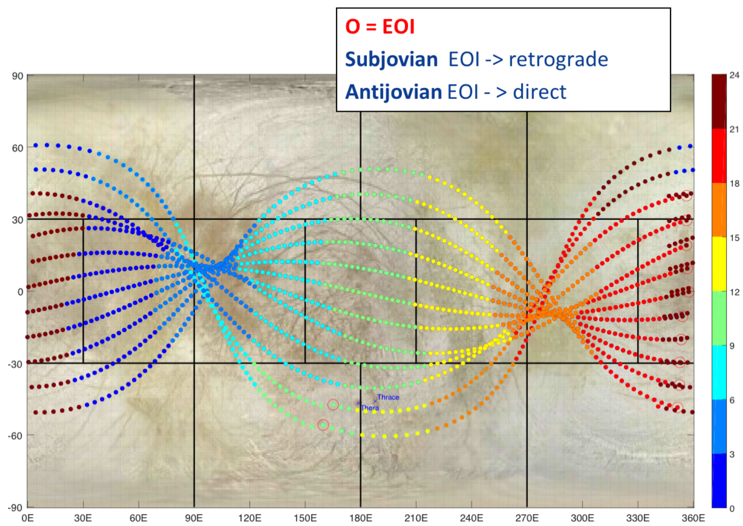

Figure 8. Attainable landing sites for a 1-GEG trajectory

Table 2. 2-GEG solutions

Comm	ID	CASE: 0/180 crossing Long	Lat	Fam	altitutde (km) after 5 km (3s) E1 error	DV cost (m/s) DVtot	TCM	EOI	V rot.	EOI + DDV	untarg. flyby alt (km)	Ganymede flyby 1 vinf (km/s)	alt (km)	Incoming (deg) pump	crank	Outgoing (deg) pump	crank	long wrt Sun	G-E Dlong (deg)	Europa flyby / EOI vinf (km/s)	alt (km)	Incoming (deg) pump	crank	Outgoing (deg) pump	crank	long wrt Sun	E-G2 Dlong (deg)	Ganymede flyby 2 vinf (km/s)	alt (km)	Incoming (deg) pump	crank	Outgoing (deg) pump	crank	long wrt Sun
DV!	1	0	-60	B	-414	1258	0	1243	15	1258	293723	2.1	1880	97	34	125	4	119	135	1.75	48	27	-11	35	87	-106	169	1.43	-631	152	-120	82	165	63
BKUP	2	0	-50	B	-1735	1233	0	1212	21	1233	218191	2.01	1663	94	34	127	5	123	138	1.7	48	24	-12	33	105	-98	166	1.38	-2004	158	-106	53	156	68
BKUP	3	0	-40	B	-1080	1215	0	1190	25	1215	185216	1.98	1991	95	33	127	5	125	141	1.67	48	21	-16	32	126	-93	163	1.34	-1361	163	-96	66	-172	69
BKUP	4	0	-30	B	-1130	1211	0	1182	29	1211	175878	1.97	2050	95	34	127	6	126	143	1.66	48	18	-20	32	144	-91	156	1.3	-1241	166	-124	61	-159	65
BKUP	5	0	-20	B	-757	1214	0	1183	31	1214	144823	1.95	2281	95	32	128	6	128	143	1.66	48	19	-20	31	160	-89	145	1.4	-1079	151	-168	51	-177	57
NOM	6	0	-10	B	-556	1217	0	1184	32	1217	67737	1.96	967	79	18	127	5	135	141	1.66	48	21	-8	28	168	-84	142	1.52	-640	145	-175	89	102	58
BKUP	7	0	0	B	-599	1227	0	1194	33	1227	9242	2.58	444	98	-34	115	1	151	130	1.67	48	24	14	26	167	-79	139	1.66	-634	138	-176	98	100	60
BKUP	8	0	10	B	-555	1241	0	1209	32	1241	5101	2.76	53	98	-36	112	1	154	130	1.7	48	26	34	27	167	-76	137	1.73	-644	135	-176	102	100	61
DV!	9	0	20	B	-528	1259	0	1229	30	1259	4388	2.73	194	98	-36	113	0	154	132	1.73	48	28	54	29	168	-74	135	1.75	-644	134	-176	103	100	61
	10	0	25	B	-518	1271	0	1243	28	1271	4114	2.7	254	98	-36	113	0	154	133	1.75	48	29	65	31	169	-74	134	1.75	-639	135	-176	102	101	60
	11	0	0	E	-542	1260	52	1175	33	1208	240903	1.37	50	90	-141	167	164	126	171	1.65	50	29	1	21	178	-63	177	1.69	-631	142	4	98	86	120
BKUP	12	0	10	E	-509	1210	0	1177	32	1210	150867	1.28	50	98	-65	173	150	126	167	1.65	50	28	2	23	-161	-67	180	1.64	-632	145	13	93	91	113
BKUP	13	0	20	E	-1506	1210	0	1179	31	1210	160974	1.25	961	100	-72	179	-77	129	165	1.65	50	28	14	22	-152	-65	178	1.69	-1671	143	15	78	112	117
DV!	14	0	30	E	-486	1217	7	1182	28	1210	164670	1.27	1618	100	-70	170	-109	127	170	1.66	50	28	39	23	-162	-63	177	1.7	-631	142	12	98	92	120
NOM	15	0	40	E	-466	1206	0	1180	25	1206	109942	1.3	1392	100	-71	167	-124	119	174	1.65	50	27	47	24	-148	-66	178	1.68	-633	143	17	96	97	116
NOM	16	0	50	E	-1729	1205	0	1183	21	1205	80088	1.29	1827	98	-75	167	-93	120	174	1.66	50	26	57	24	-138	-66	176	1.7	-2012	142	21	65	121	118
NOM	17	0	60	E	-714	1215	0	1198	16	1215	98269	1.31	1981	94	-71	160	-55	128	173	1.68	50	28	79	24	-142	-58	174	1.8	-1875	137	17	116	-170	128
NOM	18	0	70	E	-100	1211	0	1200	11	1211	88864	1.32	1182	85	-65	159	-52	128	175	1.68	50	28	87	23	-130	-57	171	1.83	-711	136	19	112	-71	133
	19	180	-50	C	123	1284	59	1245	-20	1225	182783	1.66	1765	100	78	139	34	119	168	1.75	50	31	-99	26	10	-73	144	1.9	-631	133	1	103	76	143
	20	180	-40	C	289	1237	37	1225	-25	1200	179772	1.76	1482	97	66	134	24	125	167	1.72	50	28	-118	24	13	-68	145	1.92	-631	132	1	103	75	147
	21	180	-30	C	347	1187	0	1215	-28	1187	181428	1.92	1613	97	52	129	16	130	165	1.71	50	27	-137	23	13	-66	145	1.93	-631	132	1	102	74	149
NOM	22	180	-20	C	-444	1184	0	1214	-31	1184	278660	2.07	2527	95	33	125	11	120	160	1.71	48	24	-142	26	4	-80	148	1.8	-1675	137	3	79	94	132
NOM	23	180	-10	C	-1245	1181	0	1213	-32	1181	312931	2.17	4003	95	12	123	8	116	159	1.7	48	23	-153	27	-4	-86	150	1.75	-2630	140	6	38	-170	125
NOM	24	180	0	C	-387	1178	0	1211	-33	1178	324173	2.19	3535	95	-5	122	5	114	158	1.7	48	22	-167	28	-10	-87	151	1.73	-1791	141	8	83	-98	122
	25	180	10	C	546	1180	0	1212	-32	1180	188735	1.92	1970	97	-34	128	0	131	166	1.7	48	26	166	22	-5	-63	145	1.95	-633	131	5	105	-70	152
	26	180	20	C	571	1183	0	1214	-31	1183	186643	1.91	2575	97	-33	128	-5	130	165	1.71	48	27	149	22	-6	-65	145	1.94	-632	131	5	106	-71	150
	27	180	0	D	283	1205	48	1190	-33	1157	55078	1.93	725	93	-140	133	-179	56	138	1.67	50	25	177	24	3	-81	150	1.76	-631	138	4	100	83	129
	28	180	10	D	116	1151	0	1184	-33	1151	281730	2.02	1032	93	-144	130	-176	33	139	1.66	50	20	167	29	-8	-106	158	1.5	-639	153	11	93	101	96
NOM	29	180	20	D	-1179	1152	0	1183	-31	1152	334229	2.05	1880	91	-164	130	-175	26	140	1.66	50	19	162	31	-21	-113	165	1.39	-2066	164	36	38	69	82
NOM	*30*	*180*	*30*	*D*	*-1313*	*1155*	*0*	*1183*	*-29*	*1154*	*341712*	*2.1*	*###*	*90*	*-173*	*130*	*-174*	*25*	*140*	*1.7*	*50*	*19*	*156*	*31*	*-34*	*-115*	*170*	*1.4*	*-2092*	*166*	*77*	*38*	*39*	*75*
NOM	31	180	40	D	-1238	1161	0	1186	-25	1161	316091	2.03	2319	92	-172	131	-174	29	140	1.66	50	19	155	31	-49	-111	174	1.39	-2081	162	88	38	36	74
NOM	32	180	50	D	-988	1164	0	1185	-21	1164	279760	1.99	2073	94	172	132	-172	35	142	1.66	50	19	145	31	-59	-108	176	1.41	-1965	160	83	38	54	77
NOM	33	180	60	D	-534	1172	0	1188	-16	1172	238446	1.97	1132	92	159	132	-172	40	143	1.67	50	20	141	32	-73	-103	178	1.44	-1515	157	75	50	103	80
NOM	34	180	70	D	-59	1190	0	1201	-11	1190	170306	1.93	809	93	152	134	-172	49	143	1.69	50	22	144	33	-91	-94	178	1.51	-632	151	58	88	136	88
BKUP	35	180	-60	F	-27	1218	0	1234	-16	1218	82367	1.45	1689	96	6	146	55	132	176	1.74	50	33	-100	20	22	-52	143	2.06	-693	128	-1	104	69	165
	36	180	-50	F	289	1204	3	1222	-21	1201	107892	1.46	1895	96	-3	145	43	138	178	1.72	50	32	-120	17	29	-44	143	2.11	-647	126	-2	108	69	173
	37	180	-40	F	278	1199	3	1221	-25	1195	113257	1.44	1921	97	-12	145	35	140	180	1.72	50	32	-136	16	32	-39	143	2.14	-631	125	-2	106	65	178
	38	180	-30	F	467	1193	0	1221	-29	1193	91609	1.41	1752	97	-23	147	29	139	177	1.72	50	31	-150	16	31	-38	142	2.15	-631	125	-1	108	67	179
	39	180	-20	F	239	1192	0	1223	-31	1192	65334	1.38	2520	96	-17	149	20	137	175	1.72	48	31	-163	17	27	-38	141	2.16	-1134	125	-1	106	78	-180

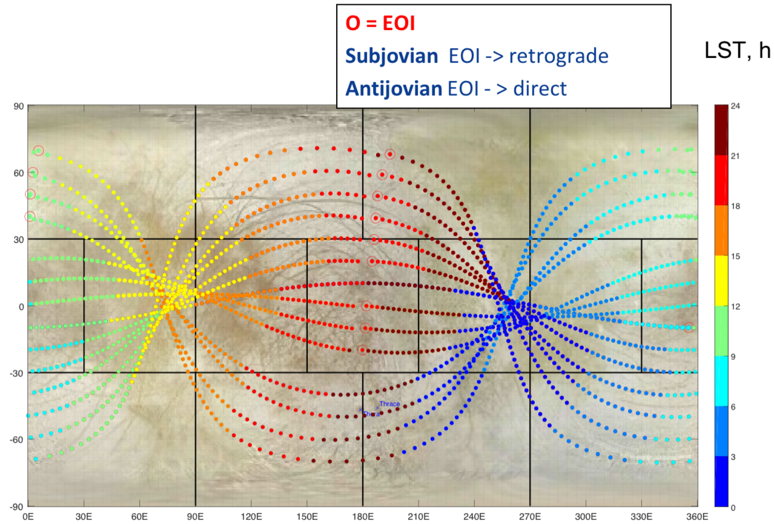

Figure 9. Attainable landing sites for 2-GEG trajectories

This section describes a method to design Lander and Clipper trajectories that meet these requirements with a three-step process:

1. We identify the flyby geometries that would meet the requirements. The driving requirement is the epoch of Clipper's closest approach, which should occur within a narrow time interval after the landing, called flyby window.
2. The flyby window is extended exploiting some flexibility on the lander trajectory design.
3. An example Clipper's extended mission is designed to target the Europa flyby satisfying the requirements (including the flyby window), and to estimate worst case scenario costs in terms of TID, ToF, Δv .

Another paper by Damon Landau[16] extends the concept of Clipper as relay spacecraft, by computing families of Clipper's extended missions in patched conics using STAR, and targeting Europa flybys to maximize the data rate over the landing region. For that study, it is assumed that Clipper and Lander trajectory can be concurrently design to adjust the flyby and landing window, which is being demonstrated in this paper.

Feasible flyby geometries

This section identifies the driving requirements for the Clipper relay flyby, using our experience from Clipper tour design. The flyby is modeled as a hyperbola parametrized by v_∞, incoming and outgoing pump and crank angles ($\alpha_{In}, \kappa_{In}, \alpha_{Out}, \kappa_{Out}$), and time of the closest approach t_{Clip}.

The second-pass requirement is enforced choosing α_{Out} corresponding to a 2:1 resonance. We also assume $\alpha_{In} = \alpha_{Out}$, so that the flyby is crank-only and has a closest approach in the middle of the landing region. This condition is not found to drive the feasibility analysis, but can be relaxed to further optimize the data link for any given LS location.[16]

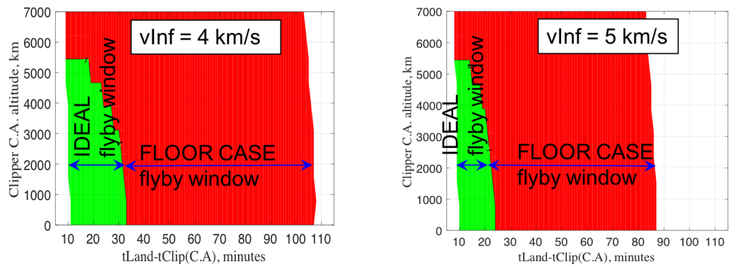

Figure 10. Flyby window

v_∞ is assumed to be 4 km/s, which is a typical value for Clipper tour, and we know can be targeted by an extended tour. We also assume the orbit before the flyby has low inclination relative to Europa's orbit, so that κ_{In} is either 0^o or 180^o, depending on whether the flyby occurs before or after the perijove.

With these assumptions, the only free parameters for Clipper flyby are κ_{Out} (or the flyby altitude) and t_{Clip}. Depending on the sign of $\kappa_{Ou} - k_{In}$, the spacecraft would fly closer to the North or South pole of Europa.

The DOV trajectory is modeled as a point hovering at 5 km above LS for 5 minutes until t_{Land} , followed by a point at zero altitude, from t_{Land} for 15 minutes (assuming spherical model for Europa). At this moment, the landing time is considered a fixed parameter, provided by the lander trajectory design. Finally, LS is assumed to be on the equator, a worst-case scenarios since it is the further away from the poles, and from Clipper flyby closest approach. The longitude is assumed to be 0^0 or 180^o, that is in the anti-Jovian or sub-Jovian hemisphere. the correct hemisphere can be targeted by choosing the incoming crank angle at 0^o or 180^o.

Clipper and Lander trajectories are then defined by two parameters only: Clipper closest approach altitude (or equivalently κ_{Out}) and the landing time delay $t_{Land} - t_{Clip}$. The two dimensional plot of Figure 10 shows the design space: each point corresponds to a Lander-Clipper relative trajectory, which can be evaluated against the requirements. The green portion of the plot is the set of solutions that meet the ideal requirements, while the red portion is the set of solutions that meet the floor requirements. The flyby window is a range of admissible t_{Clip} for which the requirements are met. Ideal requirements are met for a 20 minute flyby window, while floor requirements are met for a 90 min flyby window. During these windows, Europa true anomaly changes just 1.4^o (ideal) or 6.3^o (floor) along its orbit. We know from experience this is a narrow arc for Clipper to target in an extended tour design, so we seek to expand it using some flexibility in the landing time. Figure 11 shows the trajectories at the opening and closing of the flyby windows.

Extending the flyby window

During a typical lander trajectory design, the optimal landing time is optimized for minimum Δv and TID, while maintaining the landing site LST within $\pm 1h$ from a given value. This section shows that with negligible penalty in Lander trajectory design, t_{Land} can be varied inside three disjoint time intervals (landing windows) within a landing period, to provide an extended flyby window that Clipper can target.

We first find that the landing time can be changed within a 60 minute landing window (corresponding to 4^o in true anomaly or 17 min in LST) without significantly affecting the Δv or TID

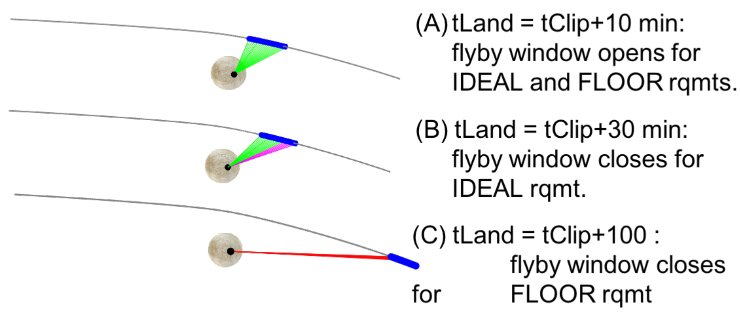

Figure 11. Allowed landing window for a fixed Clipper flyby

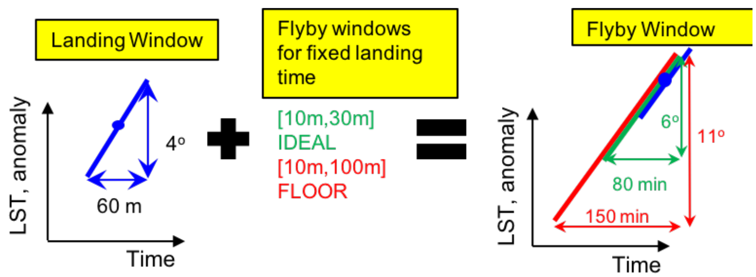

Figure 12. The landing window increase the flyby window

cost. This flexibility increases the flyby window to 80 min (ideal) or 150 min (floor), as shown in Fig 12.

Also, Figure 10 shows that the landing window repeats every week (Ganymede-Europa synodic period) for a 4-week landing period, during which the LST is within the allowed range. Clipper can then be designed to target a $4h$ extended flyby window (17^o true anomaly) shown in Fig. 14. If Clipper reaches Europa at top part of the window, then the Lander trajectory should target the first of the three landing window opportunities (option A in the figure). If Clipper reaches Europa in the mid portion or lower portion of the extended flyby mission, then the lander trajectories should target option A, B or C, (depending on real vs floor requirements). Clipper will then need to add up to two flyby and two 2:1 resonant orbits to the extended mission.

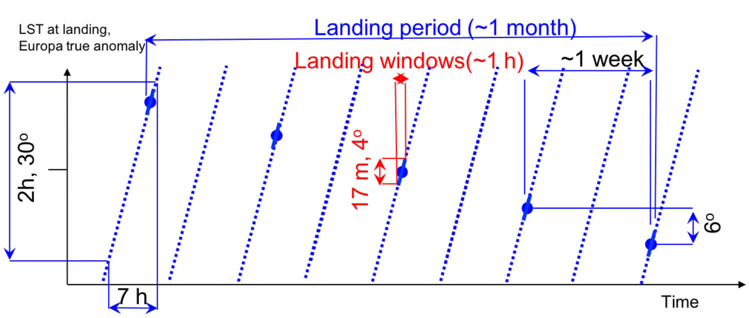

Figure 13. Landing windows within a landing period

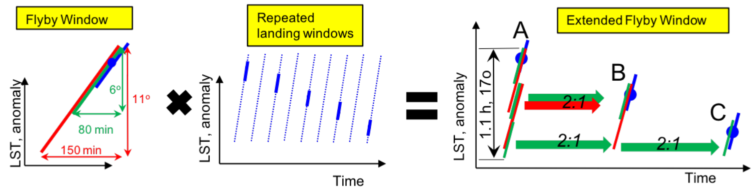

Figure 14. Fixe typo in the figure (should be 1.h)

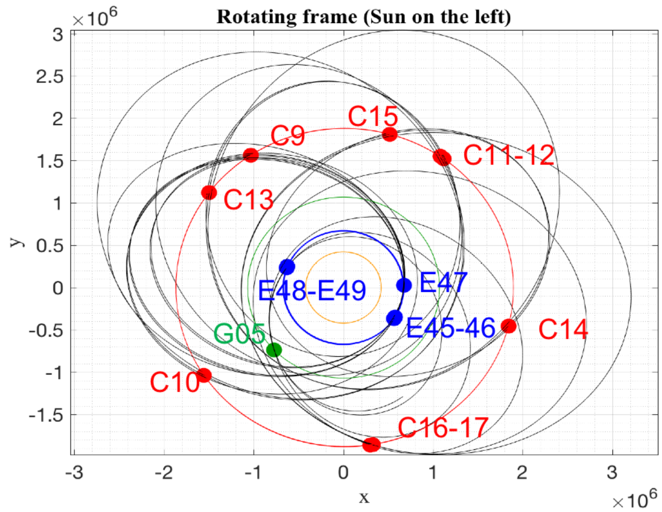

Figure 15. Example Clipper trajectory to set-up as data relay during Lander arrival

Clipper extended mission

This section shows an example Clipper extended tour that would follow the 17F17 tour.[3] The trajectory starts with the last Europa flyby of the nominal mission (E46) over the lit sub-Jovian hemisphere. The target LS is assumed to be in the anti-Jovian hemisphere, which is the most conservative case since the Clipper orbits and the location of the Europa flybys are to be rotated of 180^o . In particular the LS is assumed to be in a region near the Thera and Thrace features that were observed during the Europa Campaign 1 (E05 and E06), at a Sun-Jupiter-Europa angle of -19^o, and LST of about $11AM$. The extended tour should then target an Europa flyby at the same LST $\pm$1h, or equivalently at Sun-Jupiter-Europa angles between -27^o and -10^o .

Figure 15 shows the example tour in a rotating frame with the Sun on the left. The tour uses a Ganymede flyby and Callisto petals to rotate the spacecraft orbits and prepare the Europa flyby E48. Callisto petals are sequences of Callisto flybys patching non-resonant orbits (2:2-/1:1+ in this case).[4] E48 occurs at Sun-Jupiter-europa angle of -15^o at a $v_\infty \approx 4$ km/s and a closest approach of about 2000 km. E49 occurs two week later, for telecom back-up. Figure 16 shows the range from Jupiter and TID as function of time. This extended tour would require about 0.5 MRad TID, 40 m/s Δv, and 0.7 year. The trajectory is optimized in full model with jTOP and is designed to satisfy typical operational constraints (e.g. no flybys near solar conjunctions).

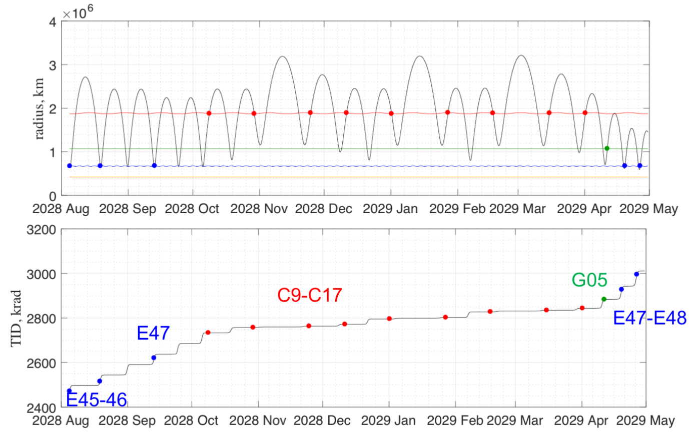

Figure 16. Extended mission costs

CONCLUSIONS

In this paper we showed how to perform the concurrent design of trajectories with tightly coupled constraints for the Europa lander DTE architectures.

The first part of the paper presents a study for the re-startable bi-props option, which enables a new strategy where the DOV executes EOI, perijove drop, de-orbiting maneuver at different times, so that multiple landing site can be reached from the same orbit. Carrier need not to execute an EOI, however, it must ballistically impact Ganymede after delivery. We found a GEG strategy that provides low TID and relatively low EOI (1250 m/s); GEG mimics Clipper's COT so LS access is similar.

The second part of the paper presents the concurrent design of the Lander tour and Clipper extended tour, such that Clipper can flyby Europa at the time of landing and act as a data relay. We found that the Clipper penalties for a TID bounding case are on the order of ˜0.5/0.6 Mrad , 40 m/s, and 9 months (for a fast 180deg rotation of the line of nodes to track landing at the anti-Jovian hemisphere). Lander has little Δv penalties, although it will have fewer tour options to choose from.

ACKNOWLEDGEMENT

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APPENDIX

The deorbiting Δv changes the spacecraft velocity to approximately match the velocity of the ground, and is therefore function of the approach orbit inclination i and of the latitude λ of the LS, as shown in the vector relations of Fig 17. In particular:

$$\Delta v^2 = v^2 + v_{rot}^2 - 2 v v_{rot} \sin \beta$$

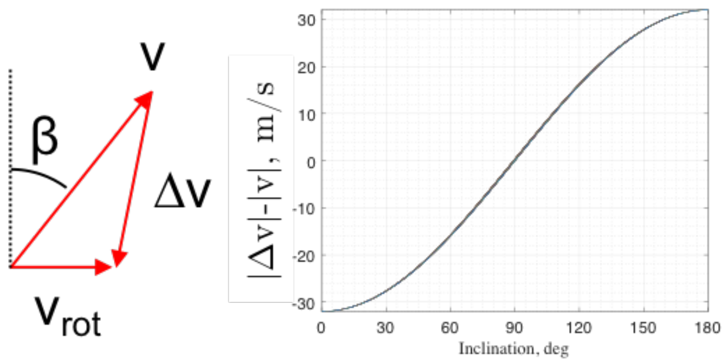

Figure 17. De-orbiting maneuver

where β is the azimuth of the velocity

$$\sin\beta = \frac{\cos i}{\cos\lambda}$$

v_{rot} is the velocity of the ground

$$v_{rot} = v_{eq}\cos\lambda$$

and v_{eq} is the velocity of a point on the equator in the inertial frame. Combining the formula yields to

$$\Delta v^2 = v^2 + v_{eq}^2\cos^2\lambda - 2vv_{eq}\cos i$$

Fr $v \gg v_{eq}$ one can simply write $\Delta v - v \approx -v_{eq}\cos i$, and the dependence on the latitude of the LS disappear. By choosing a direct rather then a retrograde orbit, one can save 20 to 65 m/s depending on the inclination, as shown in Fig. *17*.

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